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Improving landslide hazard and risk mapping in Guatemala using terrain aspect

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Abstract

Guatemala is in the path of numerous atmospheric hazards that trigger landslides by saturating mountain slopes with water reducing their safety factor. Available local studies of landslide characterization in Guatemala have indicated the importance of slope in hazard and risk mapping, but, for the most part, ignored another topographic index: aspect. However, many regional studies analyzing the effect of hurricanes on terrain show that Caribbean and Central American locations experience higher impact from hurricanes and storms on eastern, south-eastern, southern and southwestern slopes. Since hazard and risk mapping focuses on infrastructure and settlements located on slopes with various orientations, this factor needs to be addressed.

This study uses landslide data from three areas in Guatemala affected by hurricanes Stan (2005) and Mitch (1998). The results from the conducted spatial and statistical analyses show a high association of landslide prone slopes with aspect within the 76 to 260 range (i.e. eastern-southeastern-southern, and southwestern slopes). We hypothesize that this is the result of the regional wind circulation pattern governing moisture distribution. Integrating aspect in landslide analysis may improve hazard and risk mapping in Guatemala and other Central American and Caribbean regions by taking into account the regional patterns of wind circulation and the dominant role of eastern-southeastern-southwestern slopes in landslide processes.

Keywords: landslides, GIS, topography, aspect, slope, risk, mapping, hazards

1 Introduction

Landslides are a recurrent events in Guatemala due to its mountainous terrain, intense rainfall and hurricane activity from the Atlantic Ocean, and earthquakes caused by tectonic dynamics of Caribbean, Cocos, Nazca, and North American Plates. Thus landslides in Guatemala result from both, climatic and tectonic forces. However, the subject of landslides in Guatemala was not thoroughly explored until the end of the Guatemalan Civil War in 1996, when the country improved its economic and political stability which helped fostering landslide research, education, and international collaboration.

Hurricanes cause massive damages in Guatemala. According to a United Nations report (United Nations, 2005) on the effects of hurricane Stan (October 2005), its total economic impact in Guatemala was US\$983,000,000, with 719,000 hectares of land lost, probably due to flooding, landslides, and erosion. The report also indicates that most of the damage occurred in areas inhabited by indigenous populations, where the estimates of agricultural production losses were approximately 43,000,000 quetzals (approximately 5.6 million US dollars).

One of the first analytical studies on landslides was conducted by USGS scientists (Bucknam et al., 2001; Coe et al., 2004) in response to hurricane Mitch (late October – early November in 1998). Their analysis of 11,500 landslides in eastern Guatemala with slope and elevation variables showed that areas with slope less than 9 degrees were not susceptible to landslides. This conclusion excludes creep processes on terrain with low slopes (less than 9 degrees), but also includes slope categories with relatively low landslide risk (e.g. 9 – 15 degrees), which greatly overestimates risk.

The analysis of both, Mitch and Stan events is summarized by Medina (2007). This study presents data on critical slope categories obtained from Cordilleras (2007), who reports that slopes ranging from 30 to 50 degrees are highly susceptible to landslide hazards, and slopes of 15 degree or less indicate downslope areas where alluvial fans or taluses form. Interestingly, the study by Dai and Lee (2002, p.220) of landslides in Hong Kong reaches a similar conclusion: “examination of landslide frequency with the corresponding slope gradient categories shows an increase with slope gradient until the maximum frequency is reached in the 35–40° category, followed by a decrease in the >40° category”.

Large scale field studies in the municipalities of Santiago de Atitlán and Santa Catarina Ixtahuacán (both in the department of Sololá) have been conducted by the Guatemalan Coordinating Agency for Disaster Reduction (Coordinadora Nacional para Reducción de Desastres, CONRED) in 2005, and 2014 respectively (CONRED, 2014; CONRED, 2005). Both reports describe in detail landslides and their effects on local communities and use field observations data for the most part. These studies identify creep processes in populated places and hazards from landslides to local infrastructure and settlements and were used to inform resettlement programs in the region due to landslide hazards.

Later, a study from the program Integración Participativa de la Gestión Ambiental y de Riesgos en los Planes de Desarrollo y Ordenamiento Territorial del Área Metropolitana de San Salvador (IPGARAMSS, 2008) and Álvarez and Cobo (2012) introduced a heuristic approach to study Guatemala landslides using Geographic Information

Systems (GIS). Their method combines multiple GIS data to explore the relationship between each GIS data layer and landslide locations and assigns weights to each variable. The result is a unique spatial matrix with susceptible and non-susceptible hazard zone categories. This matrix is then combined with locations of dwellings or areas of urban development to create a landslide hazard or risk map that has been used for safety and preparedness decision making. In fact, these studies have become the foundation of recommendations on risk assessment and preparedness in Guatemala and El Salvador, helping local organizations (e.g. Asociación Vivamos Mejor) to use and apply scientific data to assist local communities. Both reports use high-resolution, one meter orthophoto imagery taken after hurricane Stan to identify landslide events. A large GIS database was also developed for the department of Sololá.

While the above mentioned studies have made great contributions in terms of the data developed and susceptibility mapping of landslides at regional level, they have not considered or seem to have underestimated a key topographic index: aspect. The USGS report (Bucknam et al., 2001) specifically noted that “east-to-south facing hill slopes were preferentially susceptible to landslides” but aspect was not included in the final model because the authors “were unsure about how to interpret these data.” (Bucknam et al., 2001, p. 32). However, the authors speculated about the role of hurricane Mitch in relation to the east-to-south facing slopes. The same is true for Coe et al. (2004) study which is based on the above research, and two master theses -Burchfiel (2013) and Cobin (2013), which do not consider aspect an important variable in landslide and risk analysis. The model developed by the program IPGARAMSS (2008) and Alvarez and Cobo (2012) assigned aspect the lowest importance weight (i.e., score, 0 – 10%) among others conditional factors of landslide risk, such as slope, and geomorphology.

Aspect is an important topographic index showing the orientation of slope in azimuth directions from 0 to 360 degrees and adds another spatial dimension to topographic information and hazard mapping in relation to infrastructure and settlements. For example, we can say hypothetically that slopes between 30 – 50 degrees with eastern orientations can be more hazardous than the same slope with a west or northwestern aspect. If the pattern of association of a specific aspect with landslide processes is not only local but also regional, then aspect can be considered as one of the regional risk factors. Using spatial and statistical analysis, this study examines the relation of aspect with landslide occurrences in three separate study areas in Guatemala and proposes an explanation based on wind circulation patterns in the Caribbean and Central American regions.

2 Problem Statement and Hypothesis

Aspect and slope are the most common topographic indices derived from topographic maps and digital elevation models (DEM). While slope has a direct relationship with landslide assessment as one of the main components in the safety factor, aspect does not. However, aspect influences landslide processes due to its relationship with rainfall (excessive water content) and solar radiation (regulation of soil conditions and vegetation). This makes landslides topography-controlled and water-driven hazards linked also with vegetation and landscape evolution (Poulos et al. 2012; Istanbuloglu et al., 2008; Burnett et al., 2008). All these factors are critical to landslide processes, especially

in Guatemala where landslide occurrence is tightly linked to rainfall (Medina, 2007; Coe et al., 2004; Bucknam et al., 2001).

Numerous studies in Central America and the Caribbean basin have indicated the unique characteristics of hurricane impacts on the terrain: eastern, south-eastern, southern and southwestern slopes are the most affected through erosion and tree damage due to rainfall and wind effects (Miller et al., 2013; Lugo-Perez et al., 2011; Devoli et al., 2011; Perotto-Baldiviezo et al., 2004; Rowe, 2003; Rivera and Aide, 1998; Thompson, 1983; Chinea, 1980). Since most of these studies are related to the impact of hurricanes, the general consensus among researchers is that the explanation of this association between slope aspect and hillside damages is related to the structure of hurricanes (Fig. 1) and the pattern of hurricane tracks over the region: from east to the west. Considering that in the northern hemisphere the velocity of the wind is always higher on the right side of hurricanes, this regional pattern increases the impact of wind and cyclonic rain bands on the southeastern slopes of the terrain. The main effect of this circulation pattern in relation to landslides is a decrease of the hills slope stability (which are composed of colluviums and other unsorted sedimentary material) due to increased moisture.

Fig. 1. Tropical cyclonic structure in the western hemisphere (adapted from Abbott, 2008).

However, if we look at the geographic position of Guatemala in relation to hurricane tracks, it is clear that Guatemala is located outside of the North Atlantic and Pacific swarms of hurricane tracks (Fig. 2). Therefore, we cannot apply the hurricane model on Fig. 1 to Guatemala. The hypothesis presented in this study is based on Portug (1965, p. 74) who stated that the circulation of winds produced by hurricanes along the tracks far from Guatemala follows a regional pattern and concluded that “upper-air averages indicate easterly to east-southeasterly winds at all levels from 900 millibars to 400 millibars over central Guatemala during the rainy season.”

Fig. 2. Tropical storms and hurricane tracks near Guatemala since 1887 (data source: NOAA Hurricane Center).

To place our study within the regional context, we examined the association between landslides and aspect directions in three study areas and its association with regional wind circulation and potential moisture distribution. We selected two study areas near Lake Atitlán (referred as Tzozomá and Lake Atitlán hereafter) and the one used in the USGS study (Bucknam et al., 2001) -referred as the USGS site hereafter- that includes the upper Polochic valley, central and eastern Sierra de Las Minas (Fig. 3). The two study areas near Lake Atitlán were impacted by hurricane Stan in 2005; the USGS area of study experienced effects from hurricane Mitch in 1998. Our main hypothesis is that most landslide prone slopes have an eastern or southeastern, southern, or southwestern aspect and that this is due to the influence of the local wind patterns in these areas created by the general regional wind circulation in Central America and the Caribbean Basin.

3 Study Areas

The two study areas near Lake Atitlán (Fig. 3) are within the department of Sololá, located 63 km west of Guatemala City. This department includes 19 municipalities populated mainly by K'iche' and Kaqchikel communities whose main activities are agriculture and mining (Asociación Vivamos Mejor, personal communication). The department of Sololá encompasses the volcanic range of Sierra Madre which stretches from the northwest to the southeast and the watershed basin of the river Nahualate.

Fig. 3. Study Areas.

The first study area in Sololá (Tzozomá), near Lake Atitlan is within the sub-watersheds of the Nahualate basin (known as sub-watershed Tzozomá) and includes the municipalities of Santa Catarina Ixtahuacán and Nahualá, (Fig. 3). This area includes 18 human settlements, four in the municipality of Nahualá, and 14 in Santa Catarina Ixtahuacán. The average elevation of this sub-watershed is 1500 m with an elevation ranging from 1726 m (minimum) to 3226 m (maximum). In 1999 most of the population in the main settlement of Santa Catarina Ixtahuacán was relocated outside of this sub-watershed due to the serious landslide hazards following hurricane Mitch in 1998. It is not clear however, if the damages to buildings were caused originally by creep processes and then exacerbated by hurricane Mitch, or if they were caused primarily by hurricane Mitch.

The second study area (Lake Atitlán) is located east from the Tzozomá sub-watershed (Fig. 3). The relief of the area is 2,932 m with an elevation ranging from 581 m to 3,513 m. There are three volcanoes surrounding the lake and several coastal cities scattered along the lake's shoreline.

Our third study area (USGS, Fig. 3) "includes the upper Polochic valley and surrounding highlands, the central Sierra de las Minas, the hills surrounding La Union and Zacapa, the eastern Sierra de las Minas, and the border region with Honduras." Bucknam et al. (2001, p. 1). The maximum elevation is 2,948 m. The mountains in the area consist of metamorphic, carbonate, and clastic materials. The valleys of Polochik and Montagua Rivers have scattered settlements and a road network, including two national highways.

4 Data and Methodology

The data used for the spatial and statistical analysis included orthophoto imagery, satellite data on winds obtained from the Modern-Era Retrospective Analysis for Research and Applications (MERRA) project, and precipitation data from the Tropical Rainfall Measurement Mission (TRMM). Table 1 summarizes the datasets used in this analysis, including their accuracy and source.

We first digitized landslides using the orthophoto imagery in the Tzozomá and Lake Atitlán study areas and then extracted their aspect values, which were used subsequently in the statistical analysis. The MERRA data were used to identify the wind circulation patterns during hurricanes Mitch and Stan. TRMM data were used to map daily precipitation rates during the same hurricane events, and USGS data from Bucknam et al., (2001) were used to analyze the impact of Hurricane Mitch.

Table 1 Description of the data used in this study.

Data	Source and Description	Description	Date	Spatial Resolution
Orthophoto imagery	Produced by the Guatemalan agency INSIVUMEH (Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología) and obtained from the NGO Asociación Vivamos Mejor	Collected in response to hurricane Stan (2005)	2006	1 m
Modern-Era Retrospective Analysis for Research and Applications (MERRA)	NASA Global Modeling and Assimilation Office web portal: http://disc.sci.gsfc.nasa.gov/daac-bin/DataHoldings.pl	Data represent “NASA reanalysis for the satellite era using a major new version of the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5)” (http://gmao.gsfc.nasa.gov/GEOS/). We used the dataset “MAI6NPANA” described as “MERRA 3D analyzed state, meteorology, instantaneous, on pressure levels, at native resolution” containing wind direction components U (eastward) and V (northward). (see NASA OPenDAP portal: http://goldsmr3.sci.gsfc.nasa.gov/opendap/MERRA/MAI6NPANA.5.2.0/)	1979 to 2015	0.25 degrees
Tropical Rainfall Measurement Mission (TRMM)	NASA Goddard Earth Sciences Data and Information Services http://mirador.gsfc.nasa.gov/cgi-bin/mirador/homepageAlt.pl?key word=TRMM_3B42	Daily rainfall estimates of precipitation rates (mm/day)	1997 to 2014	0.25 degrees
Digital Elevation Model (DEM)	Original DEM created by INSIVUMEH from contour line vector data derived by photogrammetry prior to hurricanes Stan and Mitch. Dataset obtained from the NGO Asociación Vivamos Mejor	Floating point data format. No information about accuracy and precision available. Similar data derived by photogrammetry by US Federal Emergency Management Agency (FEMA, 2005) show a mean error of 0.34 feet and 1.2 feet vertical accuracy	NA	15 m

Digitized landslides, derived from orthophoto imagery	Digitized manually, using ArcGIS software and orthophoto imagery collected in 2006	Landslides in Sololá and Lake Atitlán watersheds (Hurricane Stan, 2005). Accuracy close to the orthophoto (1 – 2 m). Total number of landslides in Lake Atitlán watershed: 11,167; total number of landslides in Sololá: 692	2015	1-2 m
Landslides available from USGS study (Bucknam et al. (2001))	USGS web site: http://pubs.usgs.gov/of/2001/ofr-01-0443/	ArcInfo Export format was converted into shapefile format. According to the USGS report this data were digitized from 1:40,000-scale black-and white aerial photographs taken between January 14 and March 6, 2000 with an accuracy 15 m (minimum size of the digitized landslide). Number of USGS landslides: 9,626	2000	15m

More specifically, our methodological approach followed these steps:

1. Preparation of landslide datasets resulting from hurricanes Stan and Mitch.

The data on landslides resulting from hurricane Mitch within the Sierra Minas were obtained as multiple ArcInfo (ESRI Inc.) coverages from the USGS study (Bucknam et al, 2001) and were combined in one dataset. All landslides in that study were digitized from hard copy aerial images by USGS. Because the USGS team was interested in both, landslides and their propagation path (or runout), the USGS data also contain river beds and segments of tributaries affected by landslide processes. We used a reduced version of this dataset by selecting only the landslides that had an area within the range of those occurring in our two other study areas, the Tzozomá and Lake Atitlán sites, which was less than 39,583 sq. meters. This eliminated large areas of river beds and tributaries and also made the dataset suitable for comparison with the landslides in all our study areas. The landslides in the Tzozomá and Lake Atitlán were digitized manually as polygons using landslide data (as points) from the nonprofit organizations Asociación Vivamos Mejor and Geólogos del Mundo.

2. Extraction of aspect values for each landslide occurrence.

Due to the different spatial resolution of the landslide areas (the area of the smallest one was less than 10 – 15 square meters) and the DEM derived topographic indices (standard pixel size = 225 square meters), we could not use traditional zonal statistics procedures with the aspect data in raster format. Therefore, we converted the aspect and slope data to vector format (polygons) and overlaid them with the landslide data using the vector analytical procedure INTERSECT (ArcGIS10.2, Analysis Tools). This procedure also provided a more precise calculation than resampling the DEM to a smaller pixel size. We then used summary statistics to estimate the mean slope and used a two-steps procedure to obtain the mean aspect per each landslide (see description below). Obtained data were used as an input for the statistical analysis.

The two step procedure involved: i) converting the aspect values resulting from the intersect operation from degrees to radians (degrees are not a simple linear numeric measure) and obtaining its SIN and COS values

(Eqs.1 and 2); and ii) calculate the mean aspect within each landslide polygon using the geometric function ATAN2 in Excel (Microsoft Inc.) (Eq.3), which covers all four quadrants of the standard 0 – 360 degree azimuth directions. The equations used to calculate the mean aspect of each landslide are shown below:

SIN and COS values of aspect in radians:

$$\text{SIN}(\text{ASPECT} * 0.01745329) \quad (\text{Eq. 1})$$

$$\text{COS}(\text{ASPECT} * 0.01745329) \quad (\text{Eq. 2})$$

Mean aspect in degrees:

$$\text{MEAN ASPECT} = \text{MOD} (360 + \text{ATAN2}(\text{COS}, \text{SIN}) * 180 / \text{PI}(), 360) \quad (\text{Eq. 3})$$

3. Statistical analysis of aspect

All the data were combined into one spreadsheet to perform standard descriptive statistical and histogram analysis. We define the “prevailing” slope and aspect values of each study area as a range of values within - 1 / +1 standard deviations from their mean aspect value in each study area. The statistics were calculated separately for each study area and then combined for regional analysis.

4. Spatial analysis:

We examined the spatial relationship between landslide aspect, precipitation rate, and wind direction using MERRA and TRMM data.

The data from MERRA and TRMM were downloaded as single NetCDF files for each day of the hurricane track and converted to a raster surface using ArcGIS 10.2 (ESRI). Two raster datasets were produced for each day: wind direction (from MERRA) and precipitation in mm/day (from TRMM).

Wind directions were extracted for 800 hPa (hectopascals = millibars). This corresponds to a physical elevation of 1,948 m that approximates the average level of the mountains within our study areas. The wind direction data were created by extracting the U and V components corresponding to 800 hPa and converted into wind meteorological (i.e. “from”) direction values using the following equation:

$$\text{Wind Direction (meteorological)} = 180 + (180 / 3.14) * \text{ATan2}(\text{"U_Layer"}, \text{"V_Layer"}) \quad (\text{Eq. 4})$$

The resulting wind direction surfaces were then converted into vector format (points symbolized as arrows) to visualize the daily prevailing wind direction during the hurricanes. We used the “majority” option of zonal statistics for the wind direction and the “mean” option for precipitation. The rectangle encompassing our study area (Fig. 3) was used as the zonal area for the regional zonal statistics analysis.

The following Figures (Figs. 4-7) show the wind direction during hurricane Stan on October 1 – 4, 2005 (passing 100 miles north from Guatemala), and Mitch on October 31 – November 1, when the hurricane was passing through Guatemala (Figs. 8-9).

Fig. 4. Wind directions during Hurricane Stan on October 1, 2005.

Fig. 5. Wind directions during Hurricane Stan on October 2, 2005.

Fig. 6. Wind directions during Hurricane Stan on October 3, 2005.

Fig. 7. Wind directions during Hurricane Stan on October 4, 2005.

Fig. 8. Wind directions during Hurricane Mitch on October 31, 1998.

Fig. 9. Wind directions during Hurricane Mitch on November 1, 1998.

According to our hypothesis, areas with winds from eastern-southeastern-southern and southwestern directions should have received higher levels of precipitation than other aspect directions when hurricanes Stan and Mitch passed over our study areas. To evaluate our hypothesis we analyzed the association between different wind directions and precipitation levels.

5 Results

Aspect and landslide occurrence

Table 2 presents the results from the statistical analysis of aspect for the three study areas and two hurricane events. The range of aspect values indicates that landslides occurred predominantly on east-southeastern-south-southwestern slopes within the azimuthal range of 76.2 – 260.3. This pattern coincides with the pattern of wind directions from east, southeast, south, and southwest (Table 3).

Table 2 Statistical analysis of aspect by study area.

Study Area / Hurricane / Number of Landslides used in analysis	Mean Aspect (degrees)	Standard Deviation	Range (+/- 1 Standard Deviation, degrees)
Tzozomá / Stan / 692	144.2	52.8	91.3 – 197
Lake Atitlán / Stan / 11,167	157.7	75.8	81.9 – 233.5
USGS Study Area / Mitch / 9,626	168.3	92	76.2 – 260.3

Precipitation and Wind direction

Table 3 shows the relationship between three variables: wind direction (majority), mean precipitation, and hurricane track location. As can be seen in the table, during the passage of hurricane Stan over Guatemala (October 2 – 4) the high rates of precipitation coincide with eastern, southeastern, and southwestern wind directions. Hurricane Mitch went directly through the three study areas and made landfall on Guatemala on October 31, 1998. During the landfall, the wind had a northeastern direction (azimuth = 26), however it changed to south - southwestern direction (azimuth 191 – 198) as it progressed over the Guatemalan territory; the highest precipitation rate was 33 – 73 mm/day.

Table 3 Statistical analysis of wind direction and precipitation for all study areas (combined) for hurricanes Stan and Mitch.

Date	Hurricane Track	Main (majority) wind direction, daily, azimuth (degrees)	Mean Precipitation (mm/day)
Hurricane Stan (2005)			
October 1	Northeast from Guatemala border	60	14.8
October 2	Northeast-North from Guatemala	122	10.1
October 3	North – Northwest from Guatemala	148	22.2
October 4	Northwest from Guatemala	241	34.6

Hurricane Mitch (1998)			
October 30	Approaching Guatemala	15	6.9
October 31	Landfall over Guatemala	26	32.4
November 1	Landfall over Guatemala	191	33.2
November 2	Outside of Guatemala	198.1	77.3

6 Case Study

We illustrate the applicability of our approach by using aspect and slope to map potential landslide hazards to the road infrastructure connecting settlements and farms in the Tzozomá sub-watershed (Fig. 10). While many landslides occurred in uninhabited areas, a lot of them also occurred near roads. Because roads are the primary connectors between emergency services and affected populations, their blockage could be very disruptive to disaster remediation and mitigation work, especially considering that all the roads within this sub-watershed are dirt type, narrow, and windy.

Fig. 10. Landslide hazard map of the Tzozomá sub-watershed (based on slope > 25 degrees and an aspect range of 76 – 260 degrees).

Our analysis indicates that on average, a 35 degrees slope was associated with landslides during Stan in this area, but more than 50% of landslides occurred on slopes greater than 25 degrees. Therefore, we overlaid the slope and aspect raster (GIS) layers to identify the areas that had slopes greater than 25 degrees and aspect ranges between 76 to 260 degrees (per Table 2). The result was a binary matrix where 0 represented “non-hazardous” conditions and 1 represented “hazardous” conditions. Then we combined this matrix with vector road network and evaluated results using total road network length and length of road segments within “hazardous” condition zones. Our results indicated that 23% of roads within the Tzozomá sub-watershed are vulnerable to landslide hazards. Most of them are in the eastern part of the sub-watershed (Fig. 10).

To assess our results we compared the road segments identified as “hazardous” with actual road segments impacted by Hurricane Stan. Fig. 10 shows the correspondence of landslides caused by Hurricane Stan (brown color) with the hazardous segments of the road network obtained from the model (red color). Due to the map scale and page size restrictions, it is hard to visualize this correspondence effectively. However, a spatial analysis overlaying the landslides resulting from Hurricane Stan with the roads in Tzozomá shows that out of the 3,714 m of affected roads, 2,306 m are within road segments satisfying the modeling conditions; thus resulting in a 62% correspondence between the impact derived from the proposed model and the actual hurricane.

7 Discussion

This study combines spatial and statistical analyses to evaluate the hypothesis that east-southeastern-southern-southwestern aspect slopes are more prone to the landslide occurrences due to the high accumulation of moisture on these slopes from the corresponding wind direction. We used high-resolution landslide data digitized from orthophoto imagery, aspect values from a DEM (15m), and coarse resolution wind and precipitation data from satellite imagery. Our study demonstrates that eastern, southern and southwestern range aspects values are associated with elevated landslide vulnerability in our study area. It is important to note, however, that the MERRA data are modeled. This introduces uncertainty in our results, but we currently do not have better observational or empirical data of wind surfaces suitable for this analysis.

Interestingly, the aspect range associated with elevated risk of landslides obtained in this study works better for Hurricane Stan than for Hurricane Mitch. During Mitch landfall in Guatemala the wind had an azimuth of 26 degrees, i.e. northeastern direction. However, the following day, the wind direction changed to a south-southwestern (azimuth 191) with a precipitation of 33 mm/day. This trend continued with increasing precipitation up to 77 mm/day when Mitch left Guatemala and headed north. This lag of change in wind directions can be explained by the fact that MERRA data are modeled, or by the fact that Mitch went directly through southern Guatemala while Stan passed 100 miles north of the country. This difference in hurricane passage could have created local wind circulation anomalies. Interestingly, from an historical perspective, the track of Mitch is not very common, since most historical hurricane tracks have passed through northern Guatemala or have not approached the Guatemalan territory at all (Fig. 2).

Finally, the degree to which aspect may improve hazard mapping depends on the spatial resolution of the original DEM. The DEMs used in this study were derived by photogrammetry, which is the second most accurate method after ground based topographic surveys. Recent advancements in the use and design of radars have led to relatively new elevation data such as the Shuttle Radar Topographic Mission (SRTM) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). However, their use for hazard mapping requires caution and accuracy checks due to potential horizontal accuracy errors and relatively coarse resolution (Gorokhovich and Voustianiouk, 2010; Hirano et al., 2003). Light range and detection (LIDAR) would be a better option, but much more expensive.

8 Conclusion

Aspect is an important parameter (among others) contributing to landslide susceptibility, especially when it is associated with specific wind circulation patterns. This parameter should be included in spatial or deterministic landslide models if preliminary studies show an association between its range and landslide distribution, particularly in Guatemala. Based on the literature review and our results, aspect is likely a very important parameter to consider in landslide mapping in Central America. The methodology of this study can be easily replicated by other researchers as a preliminary step to identify the potential association between aspect and landslide occurrences.

Local wind circulation in Guatemala during hurricanes and tropical storms has a strong effect on specific slopes due to the distribution of moisture. Eastern, southeastern, southern, and south-western slopes tend to receive more moisture during rainfall and also more sun radiation during the dry season. Both environmental conditions influence the occurrence of landslides by dry antecedent conditions and heavy moisture distribution during tropical storms. This combination stimulates a faster absorption of moisture by the colluvium deposits and increases the probability of landslide occurrences. In this context, the location of agricultural fields on eastern, southeastern, southern, and south-western slopes can be beneficial for agriculture (more solar radiation), but can also be risky due to their higher landslide susceptibility. This issue is particularly relevant for food security in subsistence agriculture regions, which are so common in rural Guatemala and other developing countries.

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